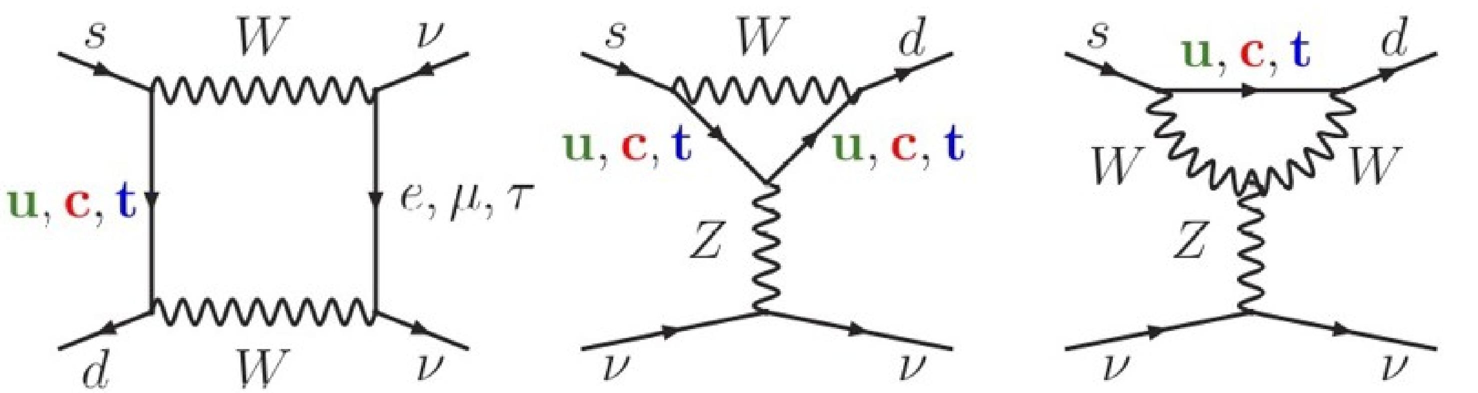
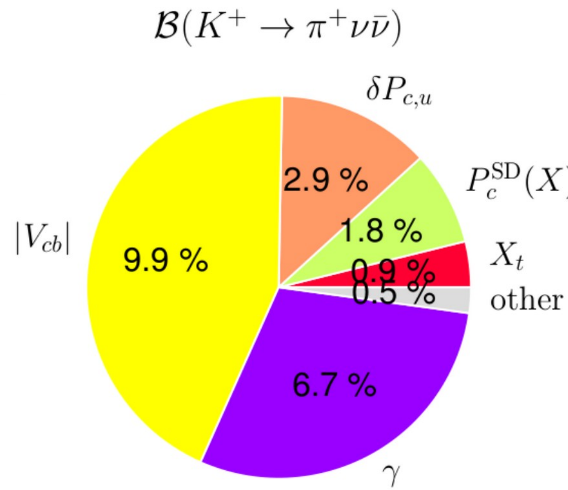
Evidence for the decay $K^+ \longrightarrow \pi^+ \nu\bar{\nu}$ from the NA62 experiment at CERN

Speaker: Radoslav Marchevski
On behalf of the NA62 collaboration

ICHEP 28th July – 6th August 2020, Prague, Czech Republic

The FCNC process $K\to\pi\nu\bar{\nu}$





Parametric uncertainty dominates

[Buras. et. al., JHEP11(2015)033]

- FCNC loop processes: s ⟶ d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays
- SM predictions: Buras. et. al., JHEP11(2015)033

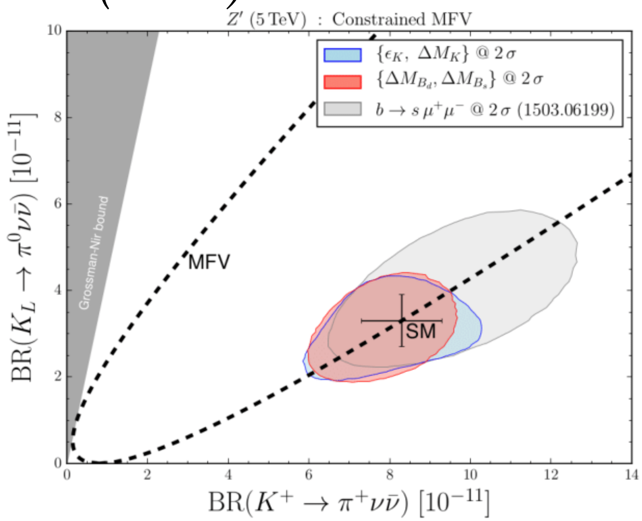
$$BR(K^+\to\pi^+\nu\bar{\nu}) = (0.84\pm0.03)\times10^{-10}\left(\frac{|V_{cb}|}{0.0407}\right)^{2.8}\left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (0.84\pm0.10)\times10^{-10}$$

$$BR(K_L\to\pi^0\nu\bar{\nu}) = (0.34\pm0.05)\times10^{-10}\left(\frac{|V_{ub}|}{0.00388}\right)^{2}\left(\frac{|V_{cb}|}{0.0407}\right)^{2}\left(\frac{\sin\gamma}{\sin 73.2^\circ}\right)^{2} = (0.34\pm0.06)\times10^{-10}$$

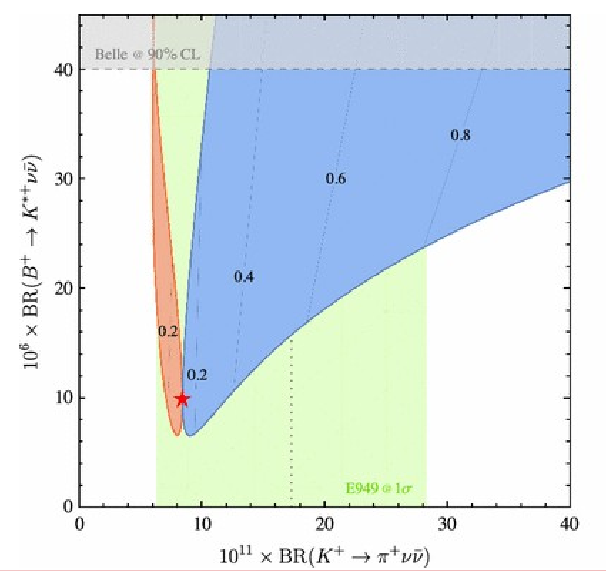
K⟶πνν̄ beyond the Standard Model

- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM analyses [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],[Isidori et al. JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models [Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- Leptoquarks [S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]
- Constraints from existing measurements (correlations model dependent)

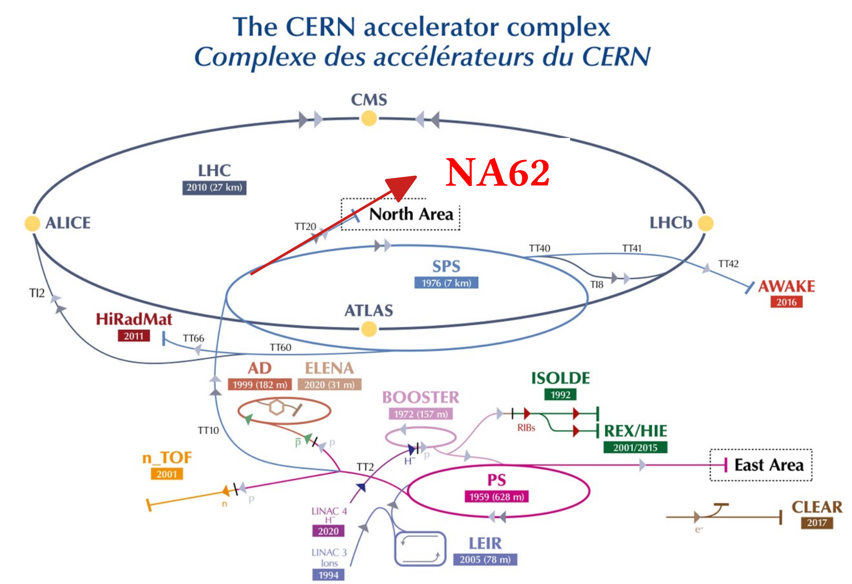
Z'(5 TeV) in Constrained MFV



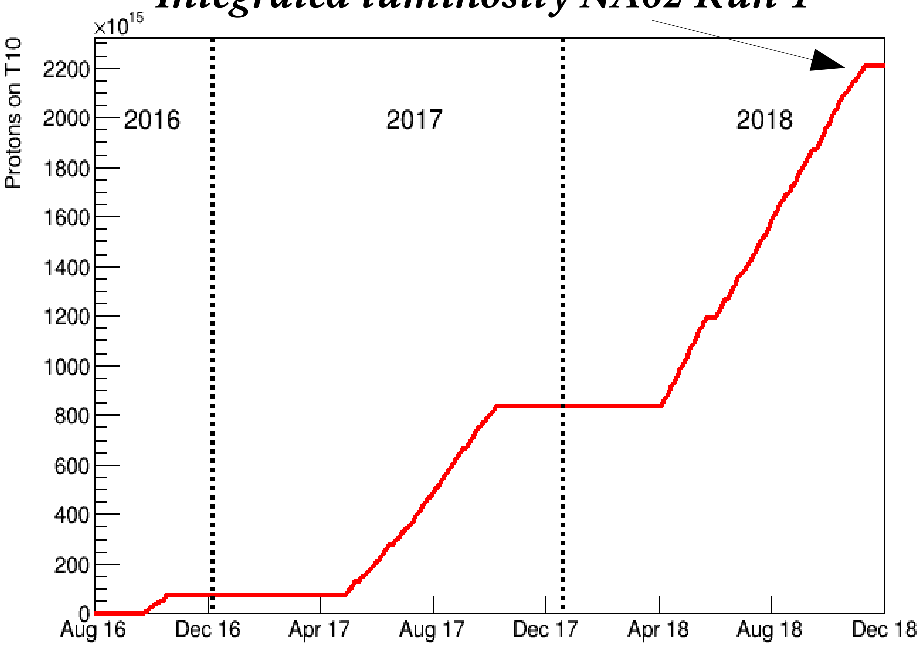
LFU violation



State-of-the-art $K^+ \to \pi^+ \nu\bar{\nu}$ experiments



Integrated luminosity NA62 Run 1



- **Past experiments (E787/E949 @ BNL)**
  - Kaon decay-at-rest technique

    $$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

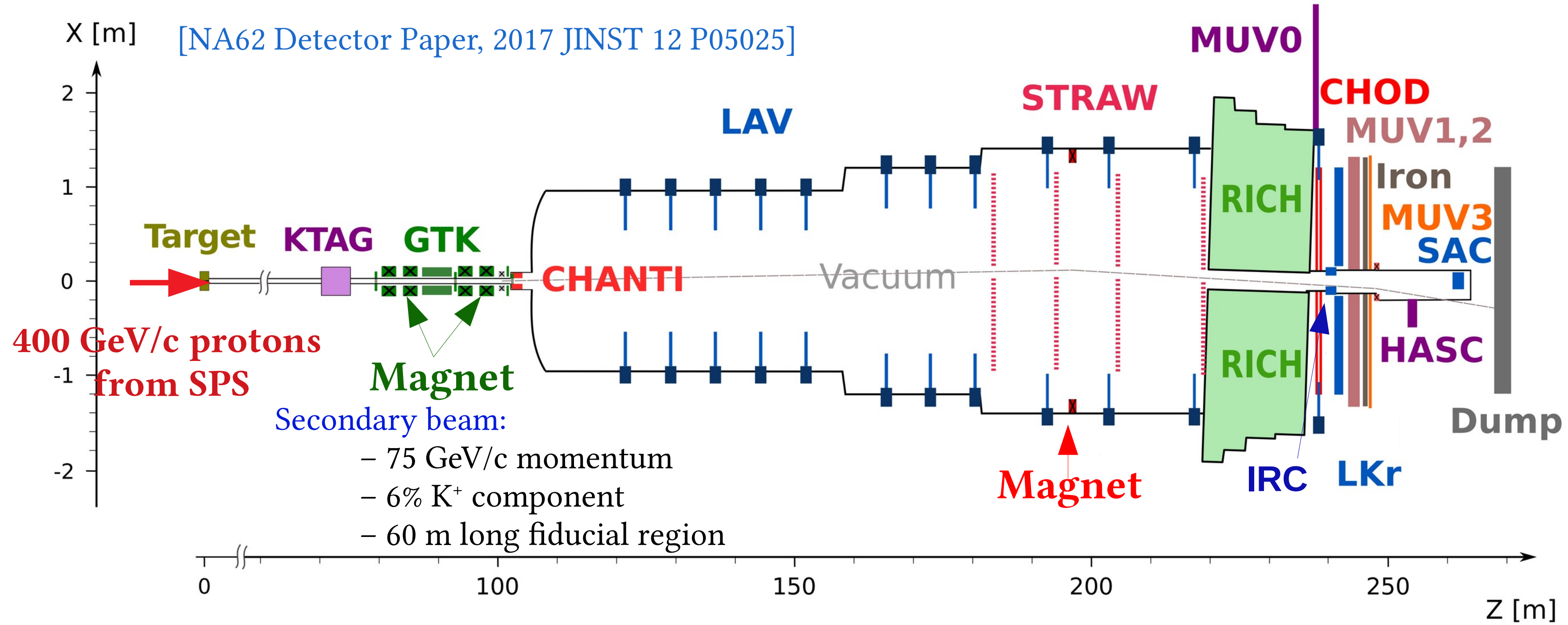
    Phys. Rev. D 79, 092004 (2009)

    Phys. Rev. D 77, 052003 (2008)

- **Present state-of-the-art $K^+ \to \pi^+ \nu\nu$ experiments**
  - Kaon decay-in-flight technique
  - NA62 experiment (this talk)

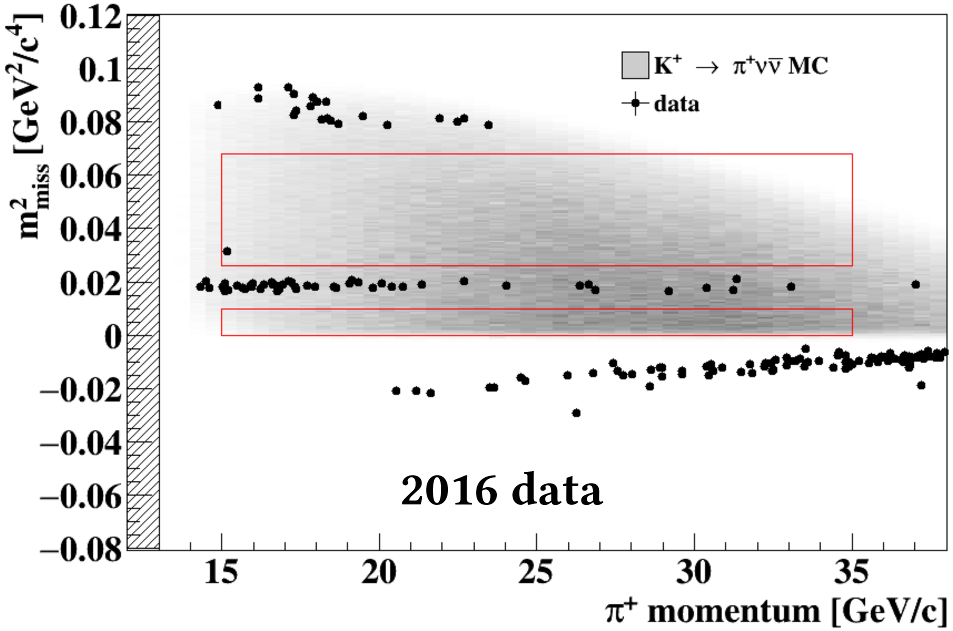
Run 1 statistics
1.9 x 10^{12} proton per spill on target
~ 2.2 x 10^{18} POT collected in Run 1

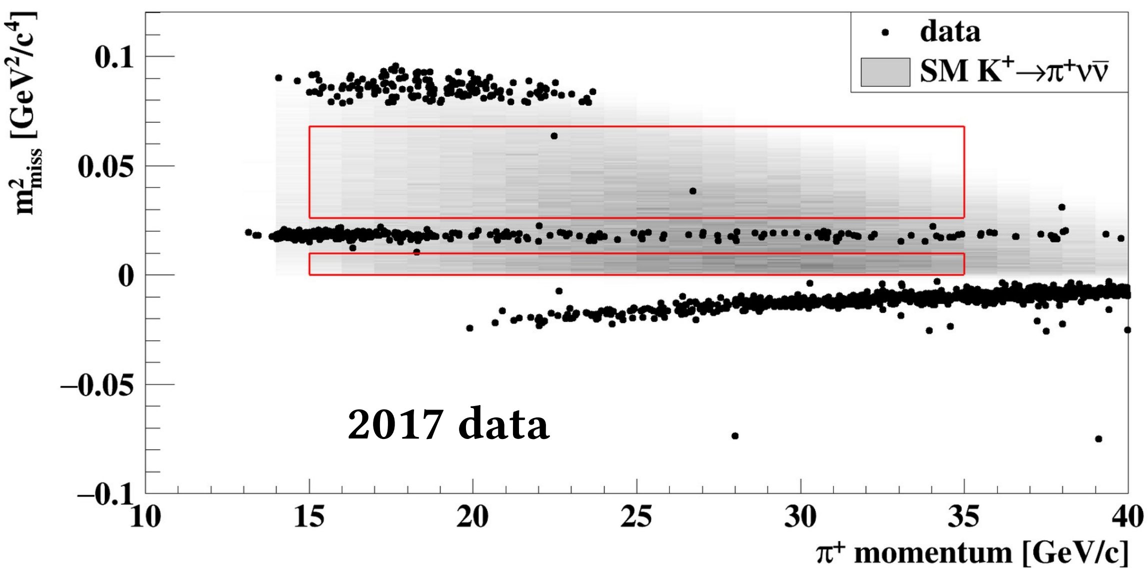
NA62 detector



- Upstream detectors (K^+):
  - **KTAG:** Differential Cherenkov counter for K^+ ID
  - **GTK:** Si pixel beam tracker
  - **CHANTI:** Anti-counter for inelastic beam-GTK3 interactions
- Decay Region detectors (π^+):
  - **STRAW:** track momentum spectrometer
  - **CHOD:** Scintillator hodoscopes
  - **LKr/MUV1/MUV2** : Calorimetric system
  - **RICH:** Cherenkov counter for $\pi/\mu/e$ ID
  - **LAV/SAC/IRC:** Photon veto detectors
  - **MUV3:** Muon veto

Reminder: 2016 and 2017 data results





- 1 events observed
- Br($K^+ \longrightarrow \pi^+\nu\nu$) < 14×10^{-10} @ 90% CL
  Phys. Lett. B 791 (2019) 156-166

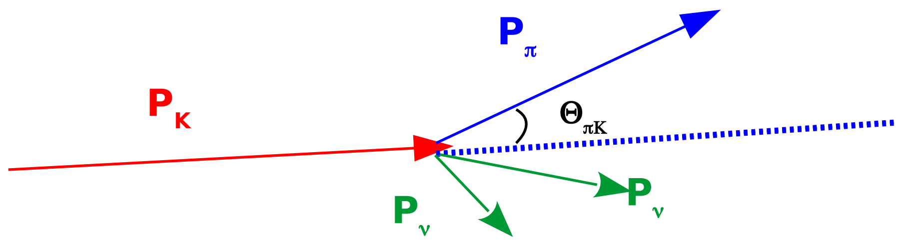
- 2 events observed
- Br($K^+ \longrightarrow \pi^+\nu\nu$) < 1.78×10^{-10} @ 90% CL
  [arXiv:2007.08218 [hep-ex]](submitted to JHEP)

Analysis strategy

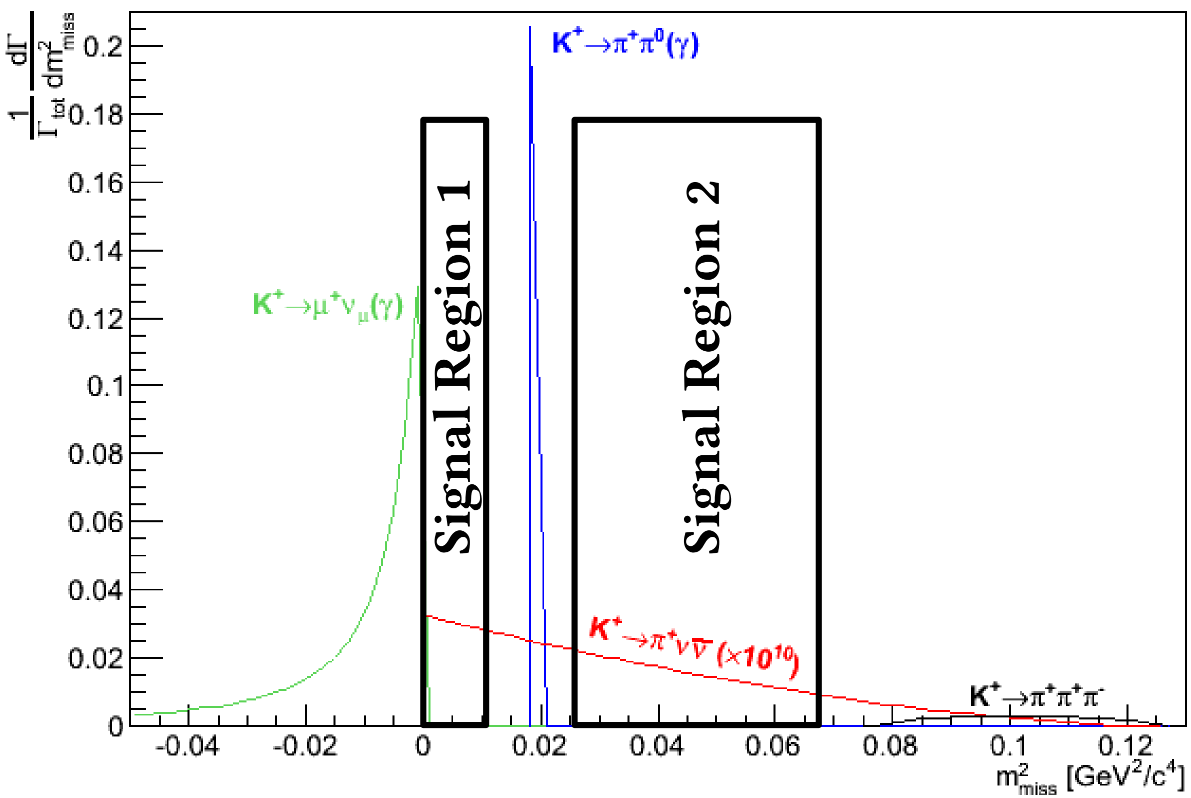
Decay-in-flight technique

$$m^2_{miss} = (P_K - P_{\pi^+})^2$$

π^+ mass assumed for the track



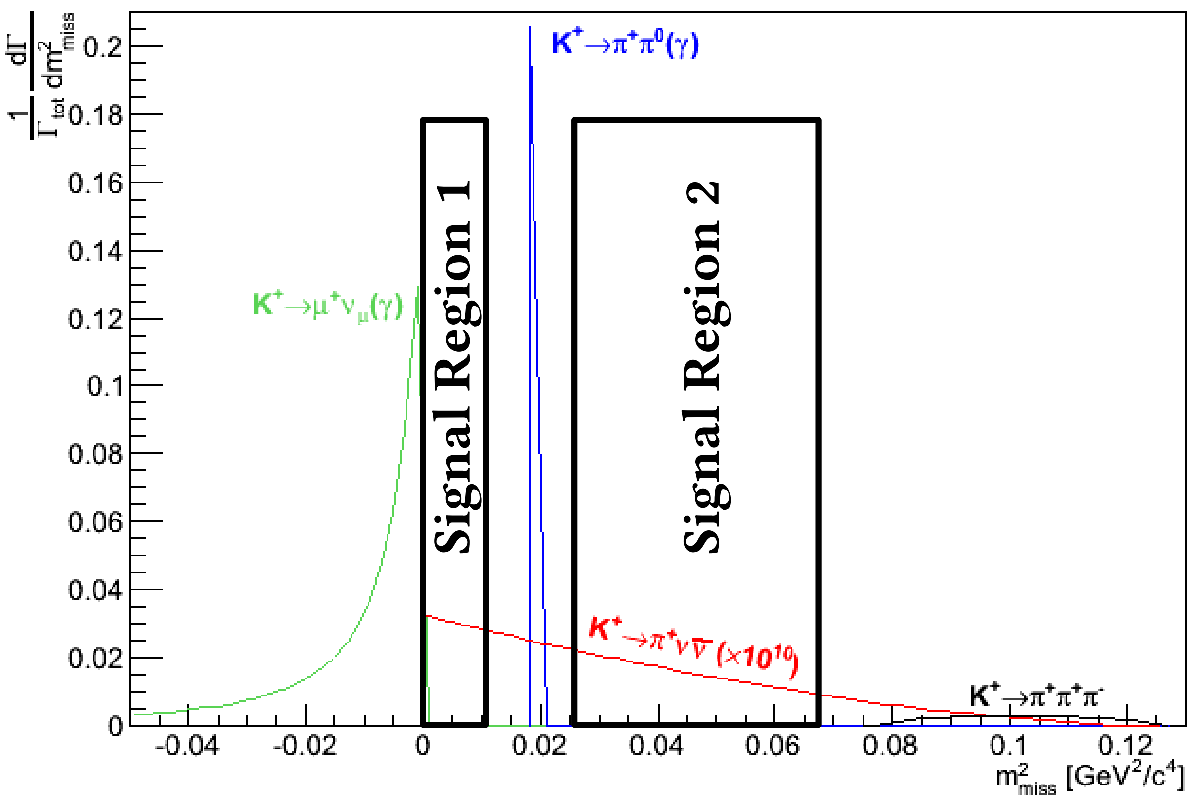
- **Muon suppression: > 10^7**
- **π^0 suppression (from $K^+ \to \pi^+\pi^0$): > 10^7**
- **Excellent time resolution: O(100ps)**
- **Kinematic suppression: ~ O(10^4)**



Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e\, \nu_e$	4.3×10^{-5}
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	**8.4×10^{-11}**

Analysis strategy

- **Analysis improvements in 2018**
  - Analysis performed in 7 separate categories
  - Category definition depends on hardware configurations (S1 and S2) and momentum
  - Selection optimized separately for each category
  - Improved signal sensitivity with respect to the 2017 analysis
  - Particle identification and upstream background rejection using MVA



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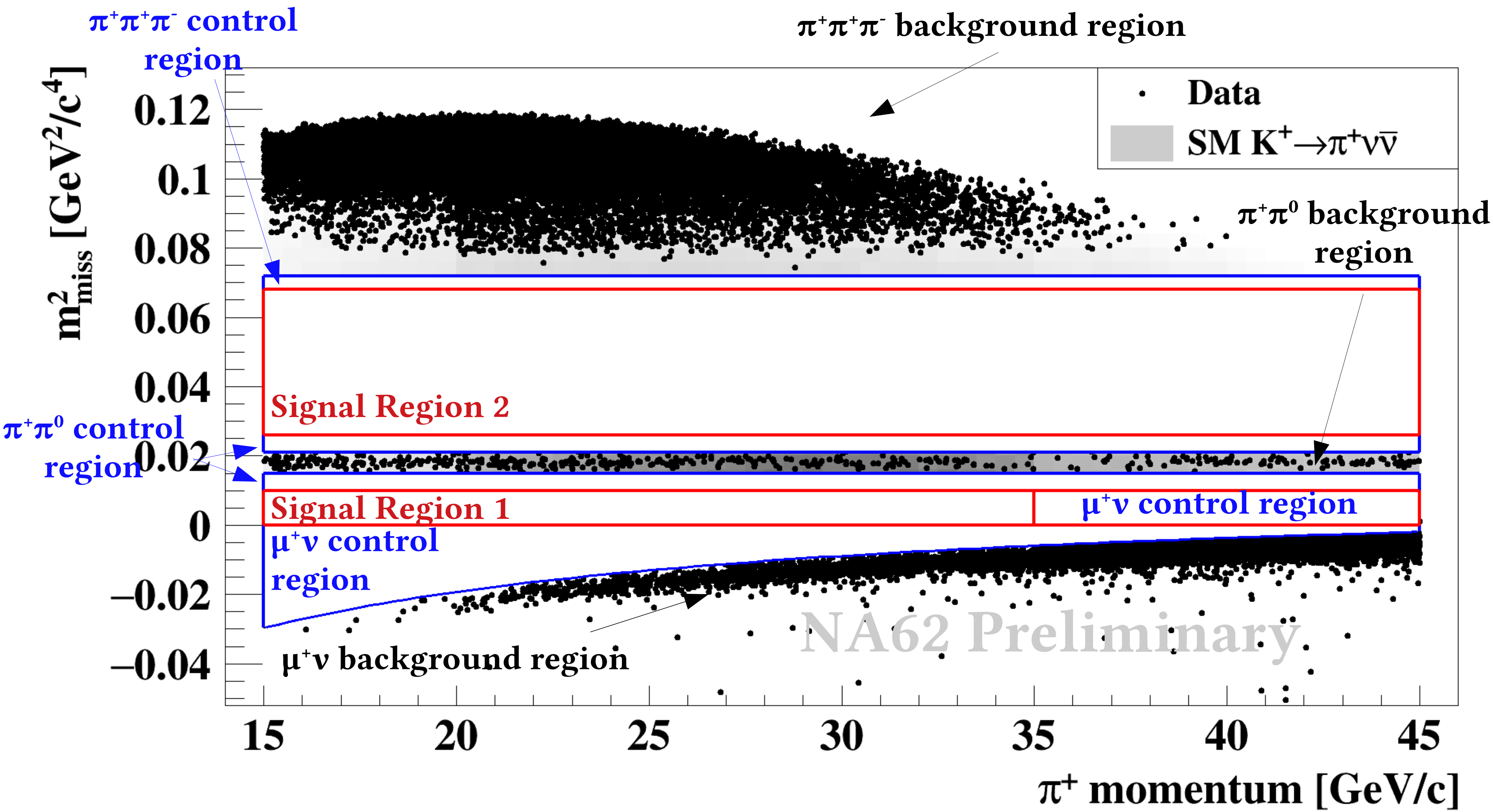
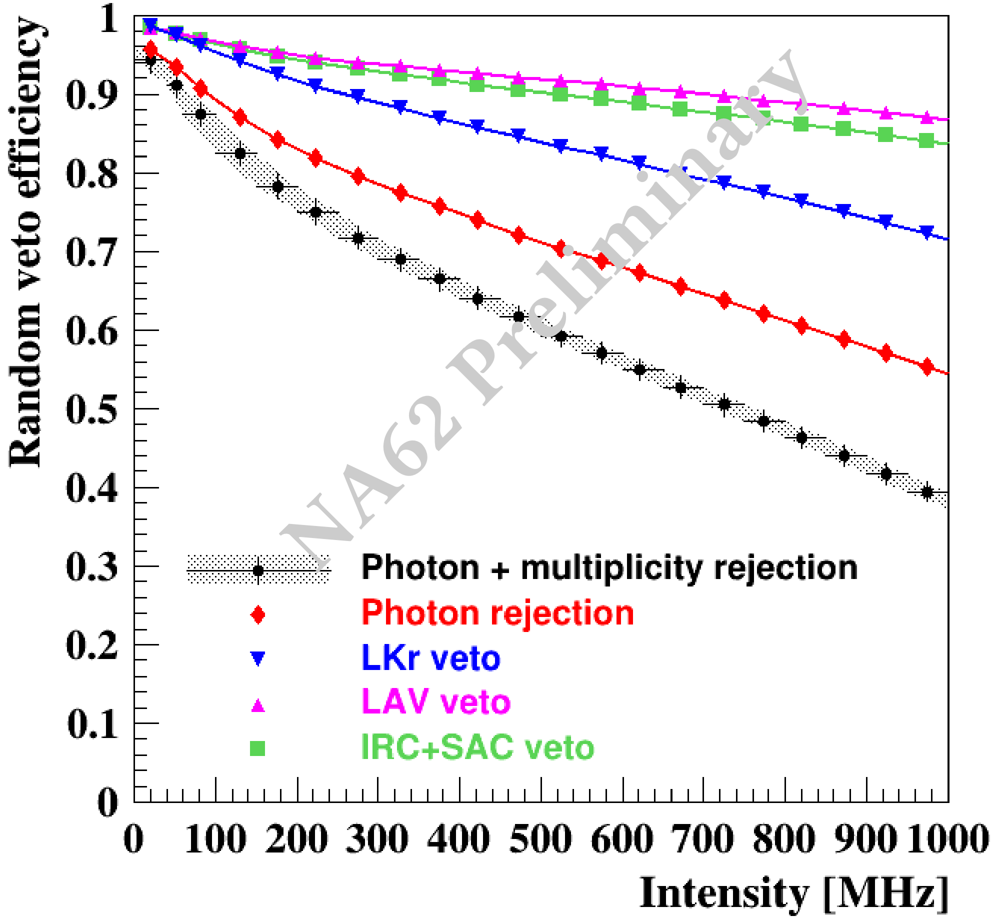
2018 data after signal selection



Single Event Sensitivity

$$N_{\pi\nu\nu}^{exp} \approx N_{\pi\pi}\epsilon_{trigger}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \Longrightarrow \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$



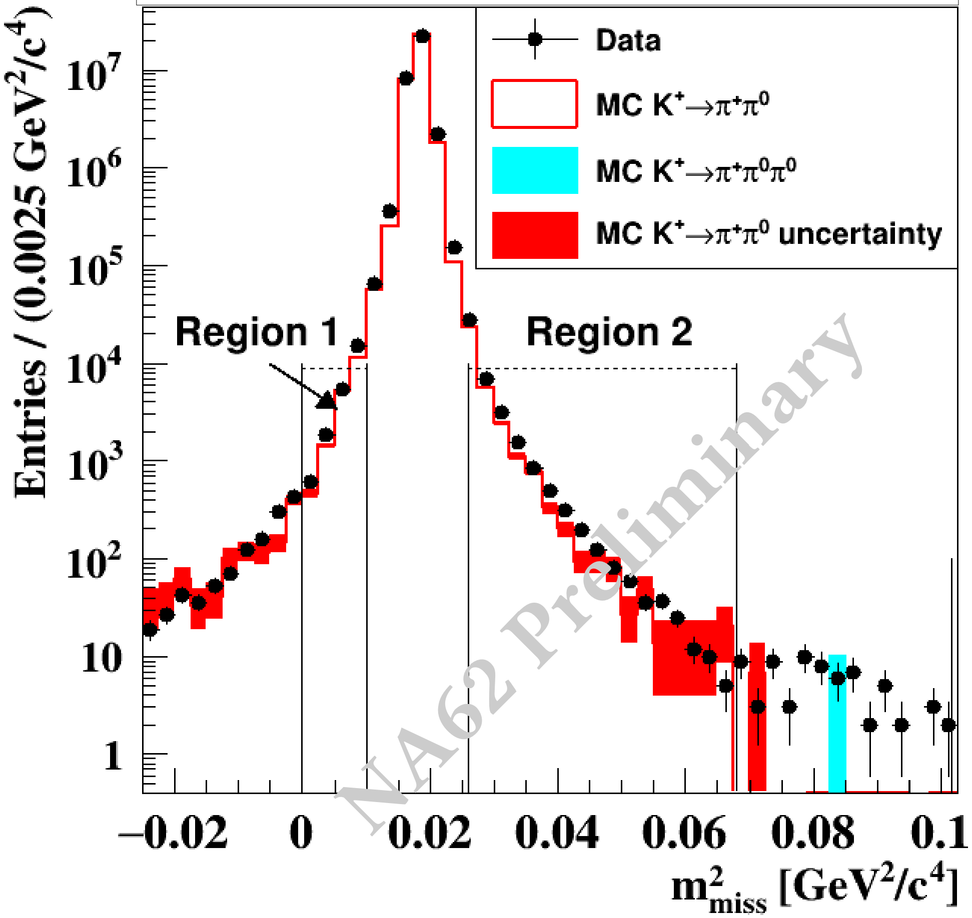
	Error budget S.E.S.
Trigger efficiency	5%
MC acceptance	3.5%
Random Veto	2%
Background(normalization)	0.7%
Instantaneous intensity	0.7%
Total	**6.5%**

- $K^+ \to \pi^+\pi^0$ decay used for normalization
- Cancellation of systematic effects (PID, Detector efficiencies, kaon ID and beam-related acceptance loss)

$$S.E.S. = (1.11 \pm 0.07_{syst.}) \times 10^{-11}$$

Background from kaon decays

Control $K^+ \to \pi^+\pi^0$ data used to study the tails of the m^2_{miss} distribution



Data in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection (including π^0 rejection)

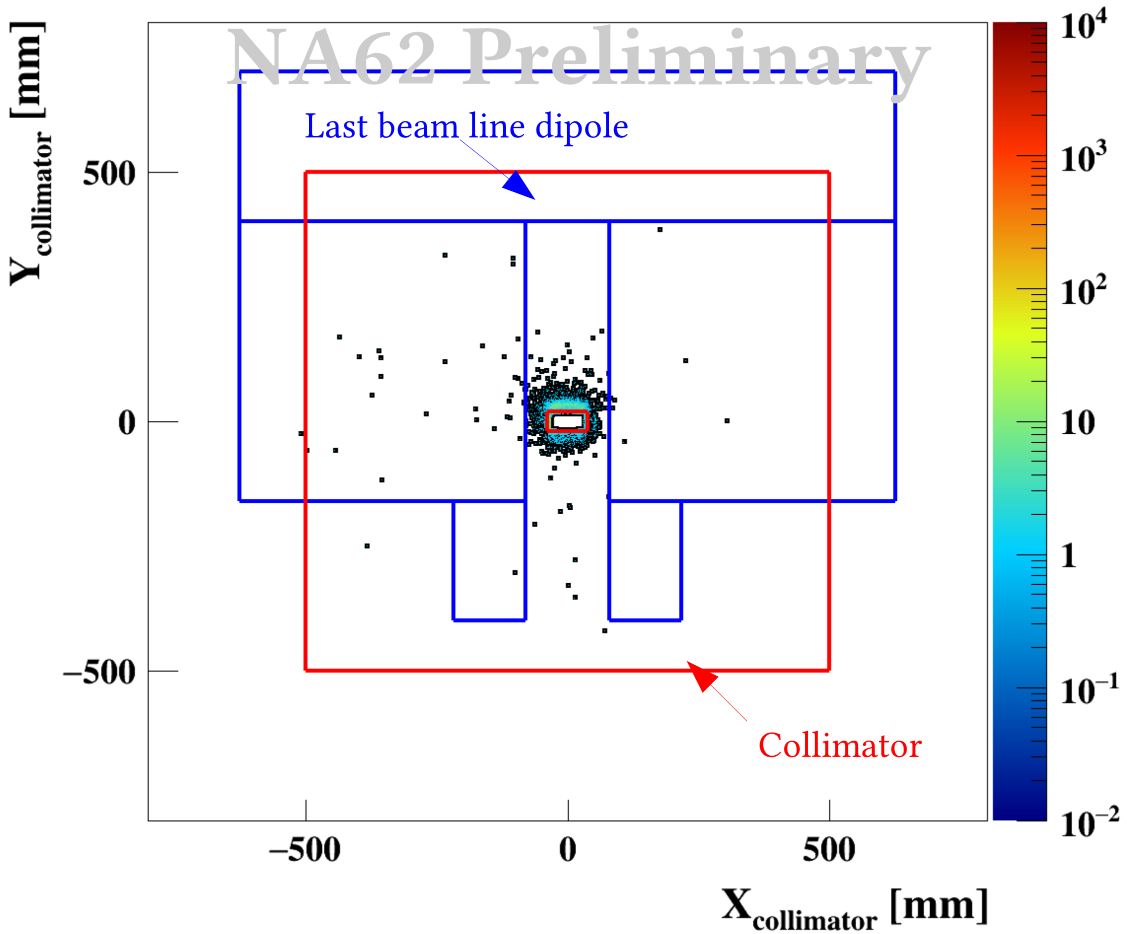
$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f_{kin}(region)$$

Expected $K^+ \to \pi^+\pi^0$ in signal regions after the $\pi\nu\nu$ selection

Fraction of $\pi^+\pi^0$ in signal region measured on control data

- Same procedure used for $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^+\pi^-$ backgrounds
- $K^+ \to \pi^+\pi^- e^+\nu_e$ estimation entirely using MC simulations normalized to the S.E.S.

Upstream background



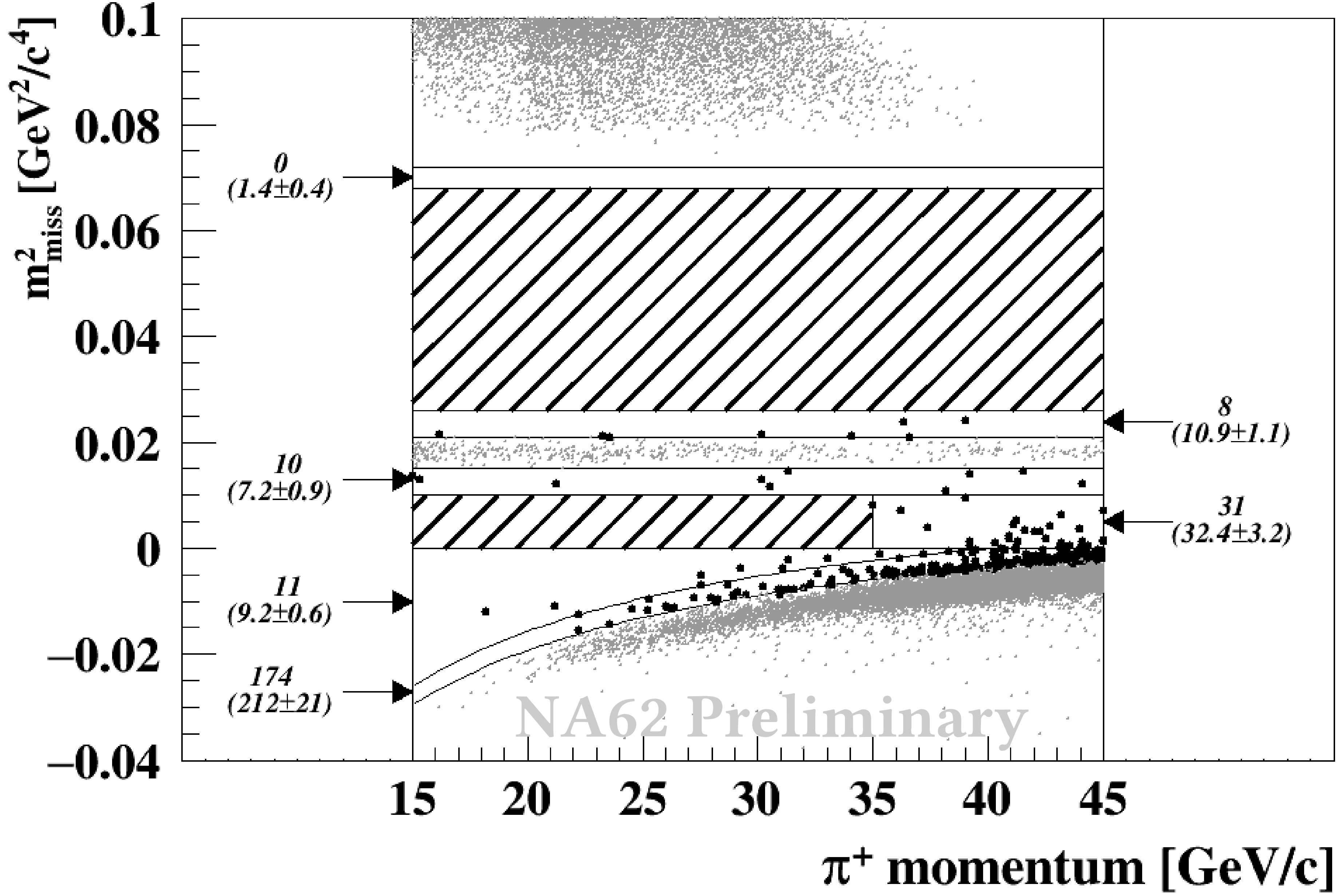
- Pions produced upstream of the fiducial volume (FV)
  - Early K^+ decays (upstream of the FV)
  - Interactions of beam particles with the beam spectrometer material
- Detected pions are associated to an accidental particle from the beam line
- Dangerous if coupled with pion scattering in the first spectrometer chamber
- Kaon-pion association and geometrical cuts effective
- The geometrical origin of those events allows us to define samples for background validation
- Data driven background estimation

Total expected background

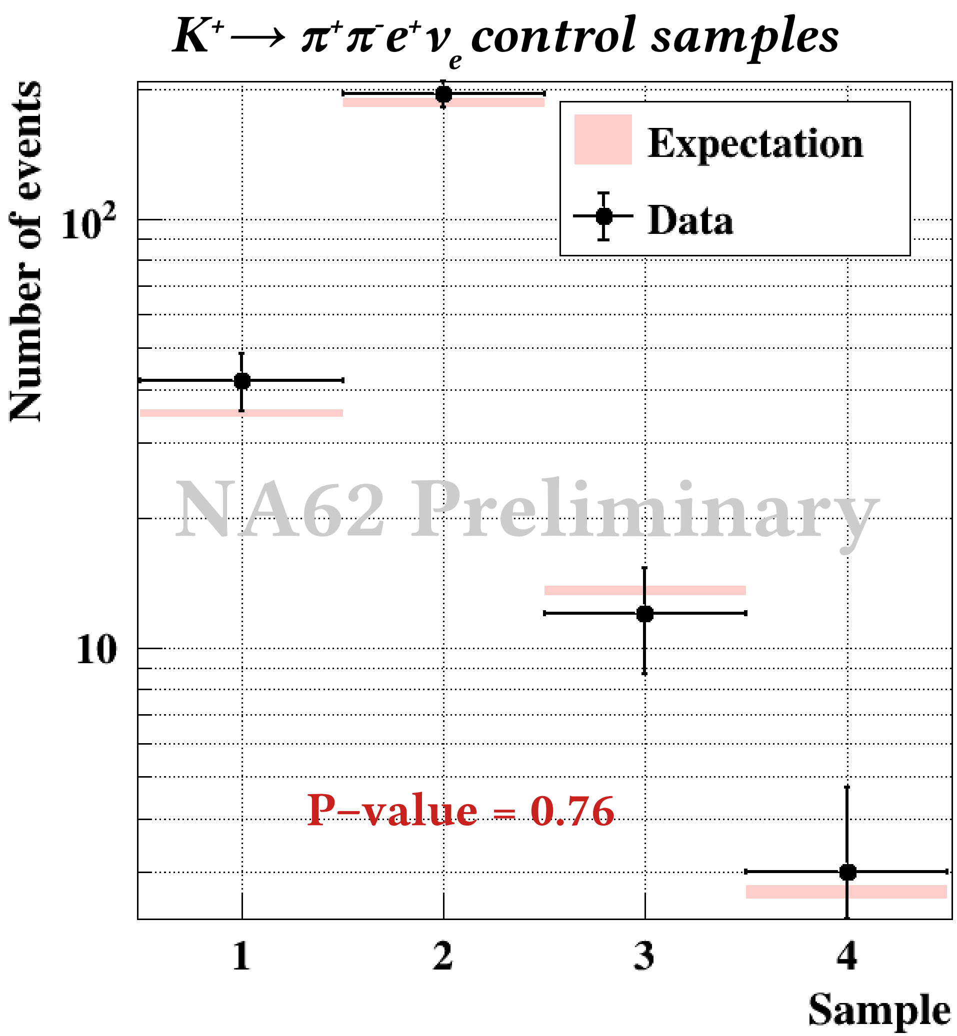
	2018 data
Expected SM signal	**$7.58(40)_{syst}(75)_{ext}$**
$K^+ \rightarrow \pi^+\pi^0(\gamma)$	0.75(4)
$K^+ \rightarrow \mu^+\nu(\gamma)$	0.49(5)
$K^+ \rightarrow \pi^+\pi^-e^+\nu$	0.50(11)
$K^+ \rightarrow \pi^+\pi^+\pi^-$	0.24(8)
$K^+ \rightarrow \pi^+\gamma\gamma$	< 0.01
$K^+ \rightarrow \pi^0 l^+\nu$	< 0.001
Upstream	$3.30^{+0.98}_{-0.73}$
Total background	**$5.28^{+0.99}_{-0.74}$**

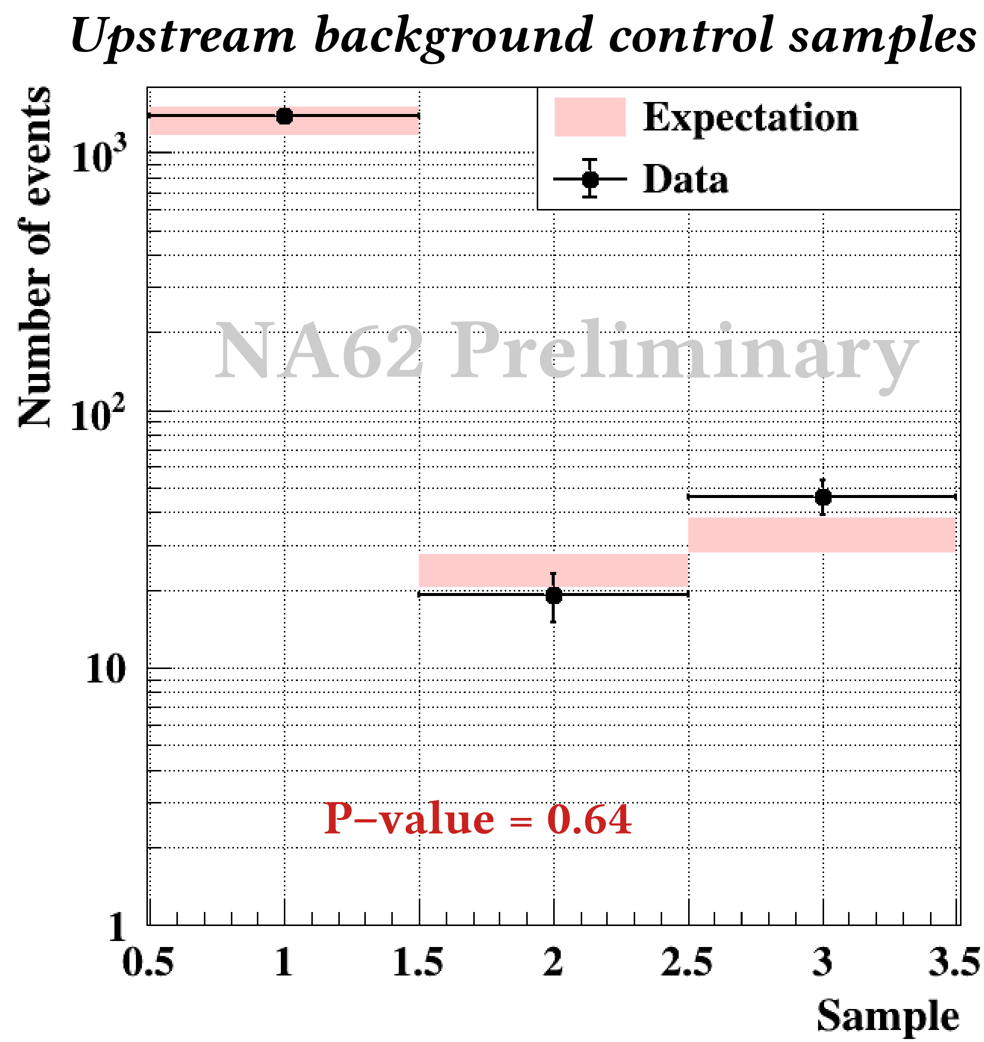
- Background expectations validated in control regions using a blind procedure

Control regions: $K^+ \to \pi^+\pi^0$, $\mu^+\nu_\mu$ and $\pi^+\pi^+\pi^-$



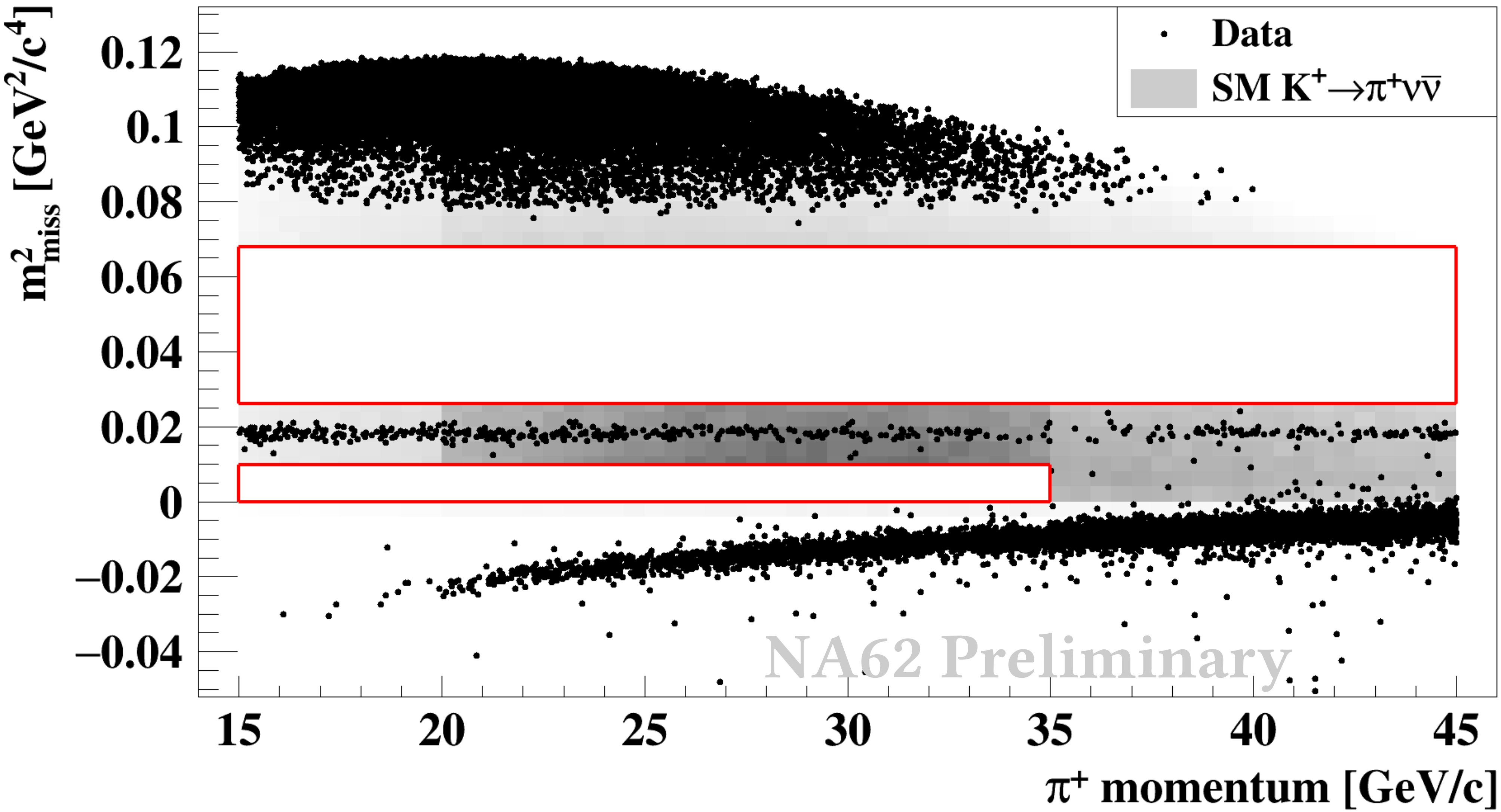
Control regions: $K^+ \to \pi^+\pi^- e^+\nu_e$ and upstream



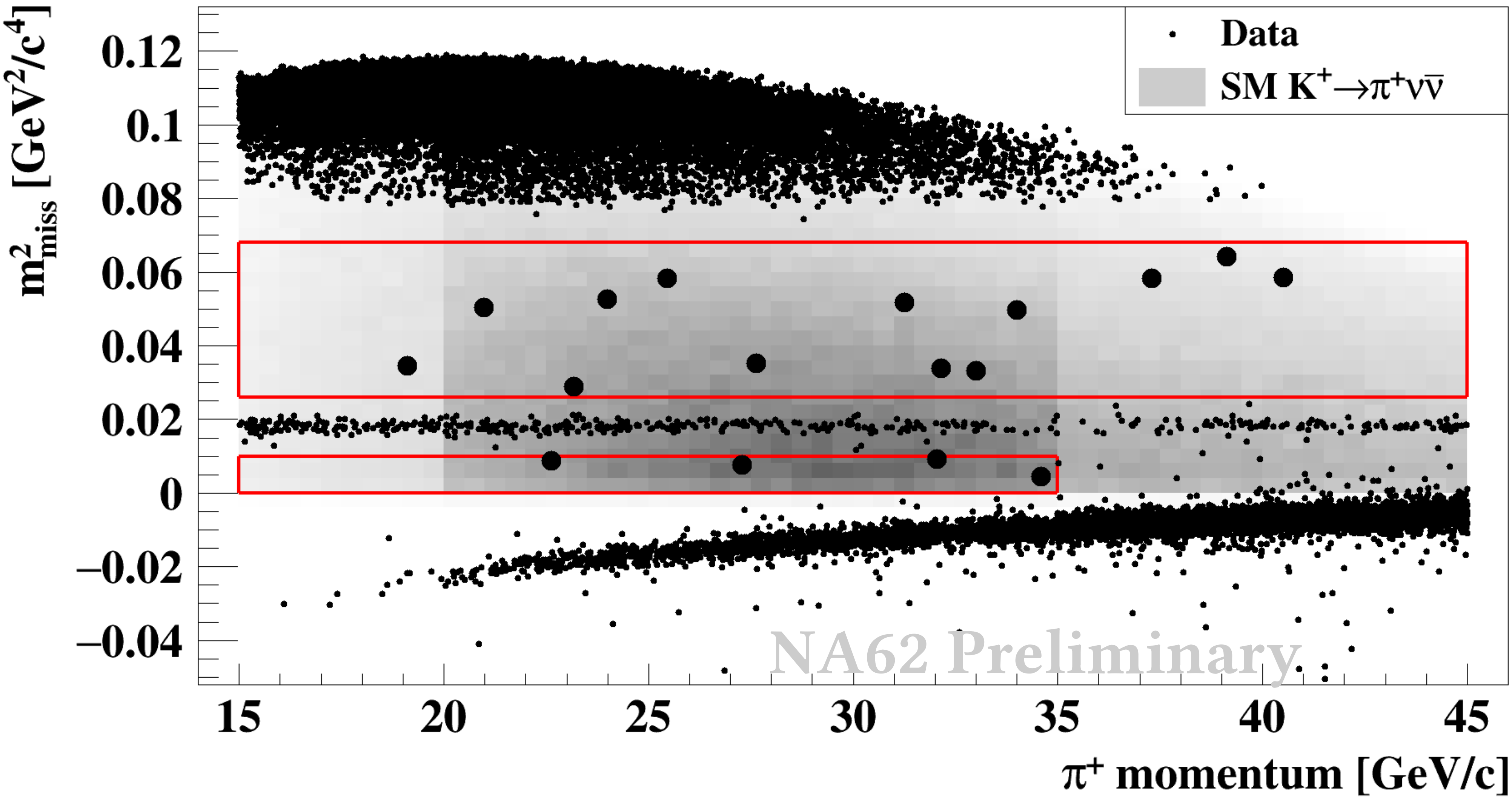


- Data samples defined by inverting signal selection criteria
- The sensitivity of some control samples comparable to the S.E.S.

2018 data before unblinding

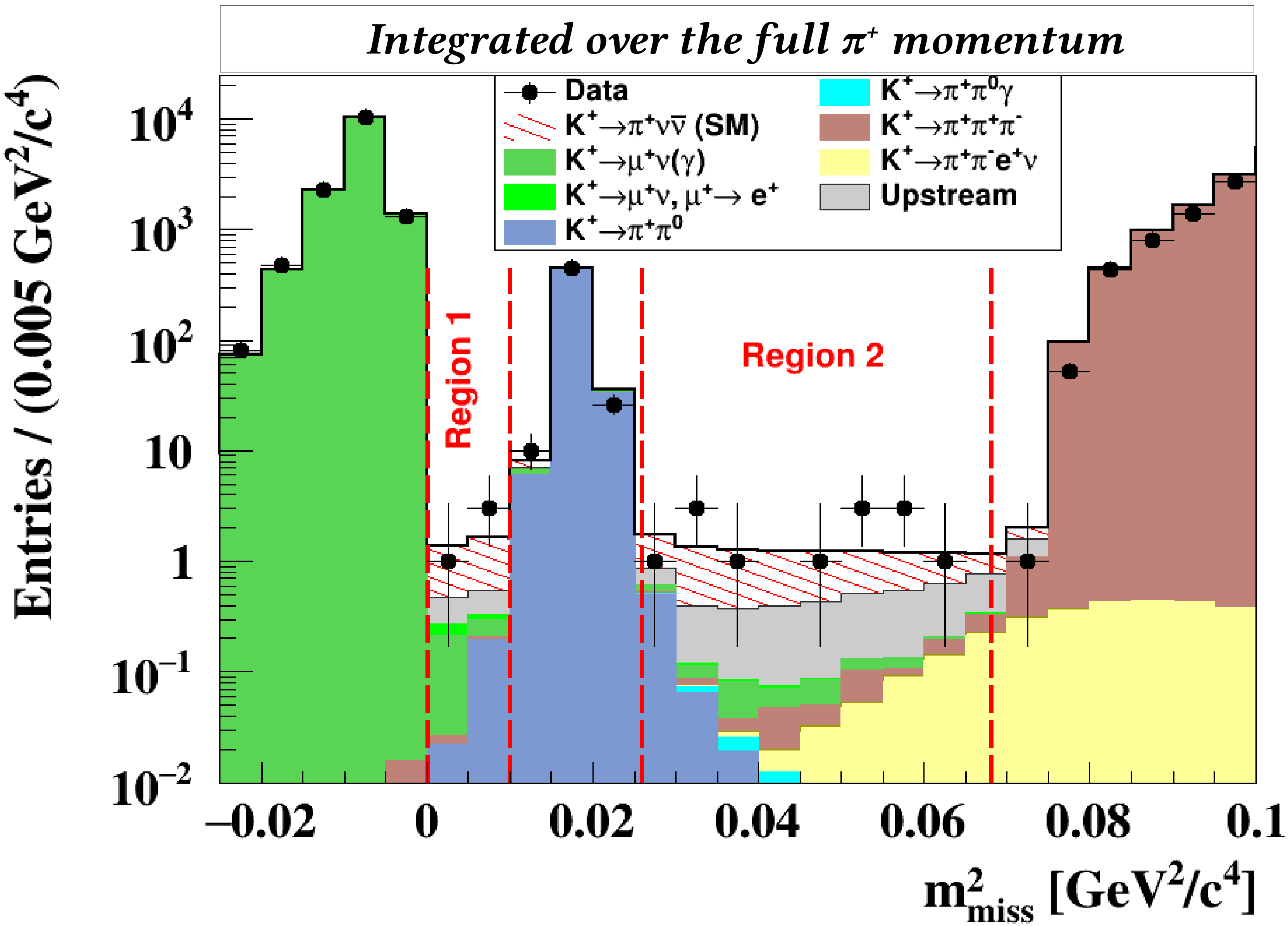


Opening the box in the 2018 data

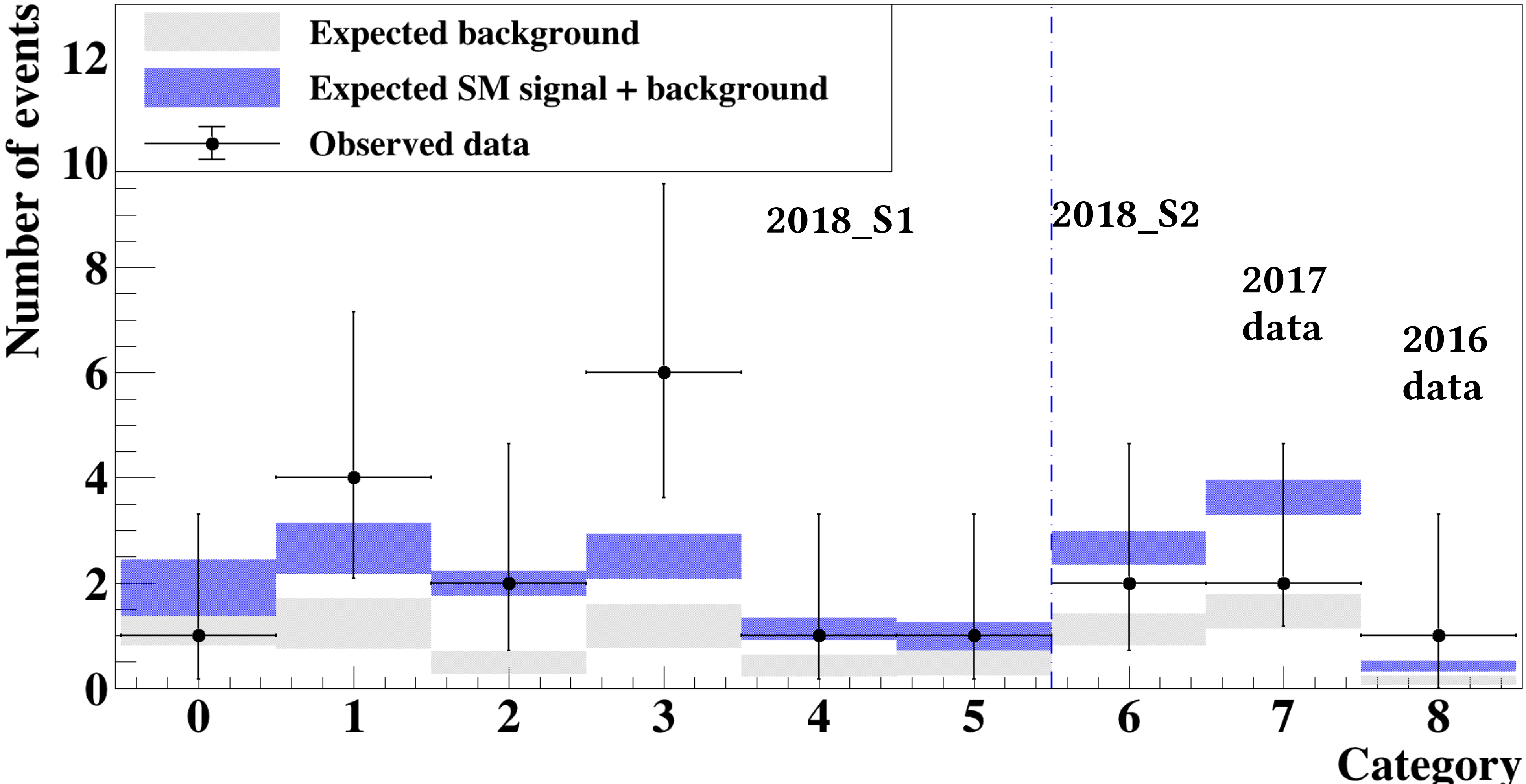


5.3 background + 7.6 SM signal events expected, 17 events observed

m^2_{miss} signal and background in the 2018 data

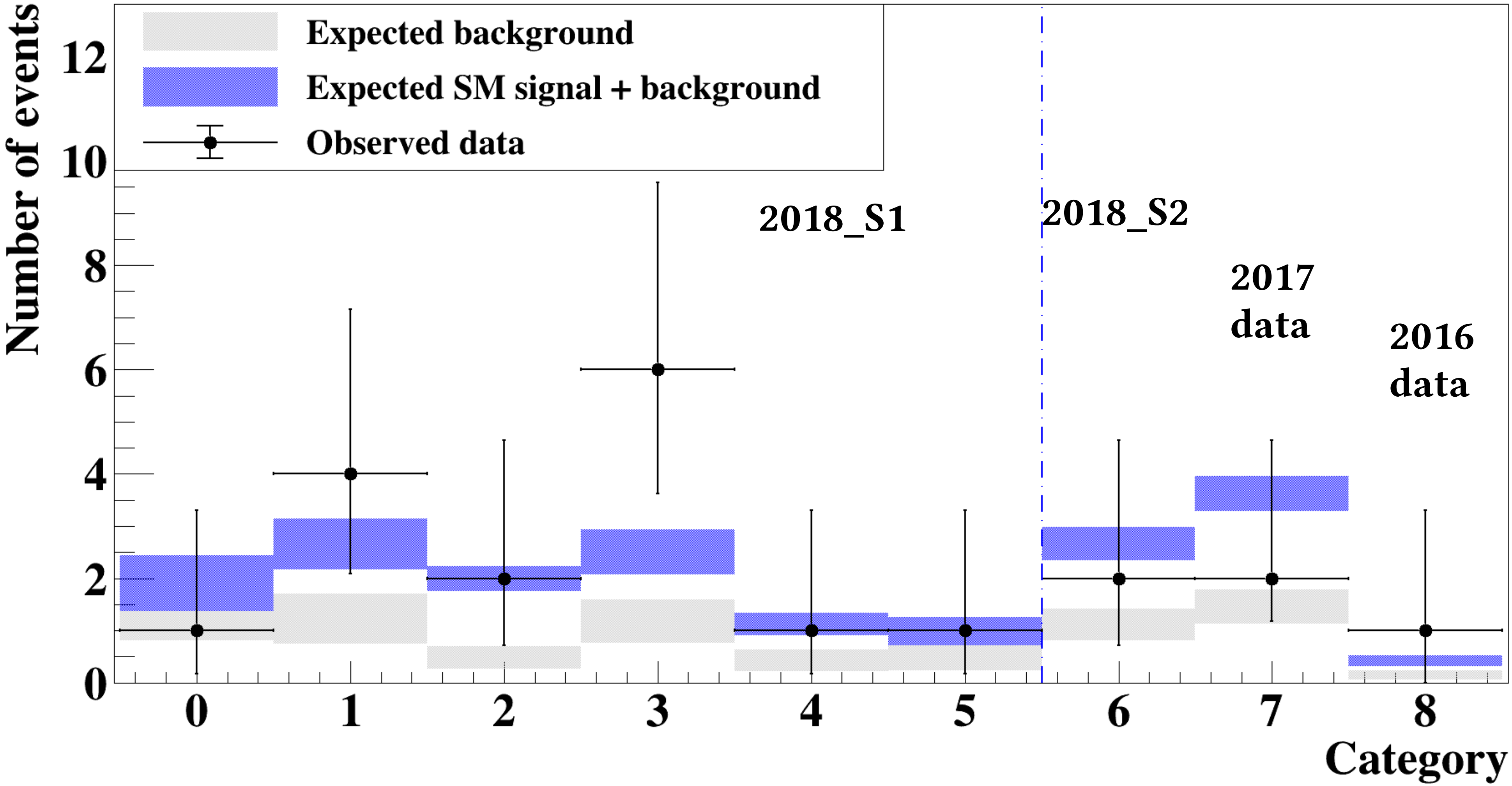


Results



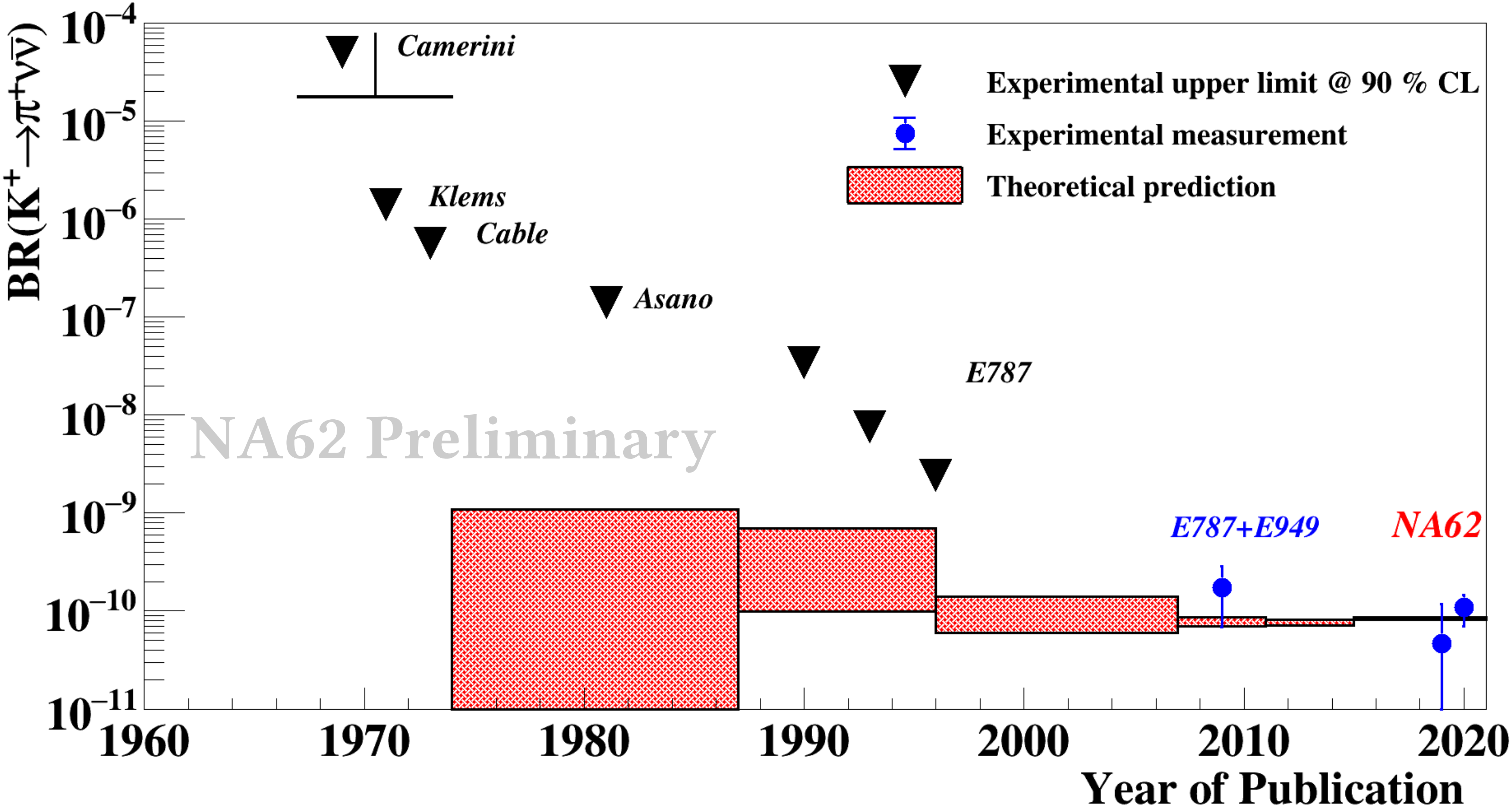
- Maximum likelihood fit using signal and background expectation in each category
- Two samples with different hardware configurations in 2018
  - 2018_S1 ~ 80% of the 2018 dataset, 5 GeV/c wide bins from 15-45 GeV/c
  - 2018_S2 ~ 20% of the 2018 dataset, integrated over momentum
  - 2016 and 2017 datasets, integrated over momentum added as separate categories

Results

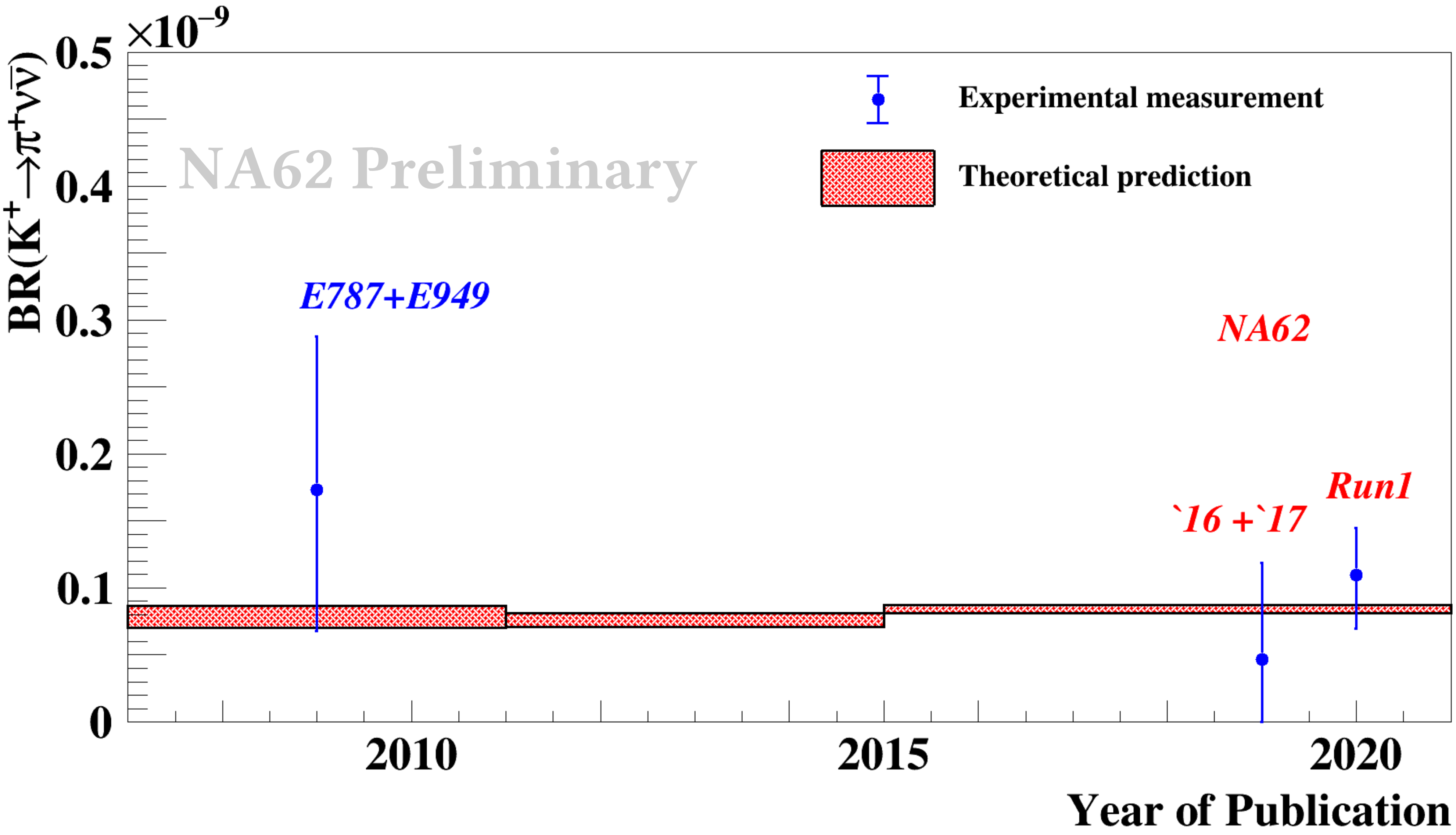


- **NA62 Run1(2016 + 2017 + 2018) result:**
  - $Br(K^+ \to \pi^+ \nu \bar{\nu}) = (11.0^{+4.0}_{-3.5\,stat.} \pm 0.3_{syst.}) \times 10^{-11} (3.5\sigma \text{ significance})$

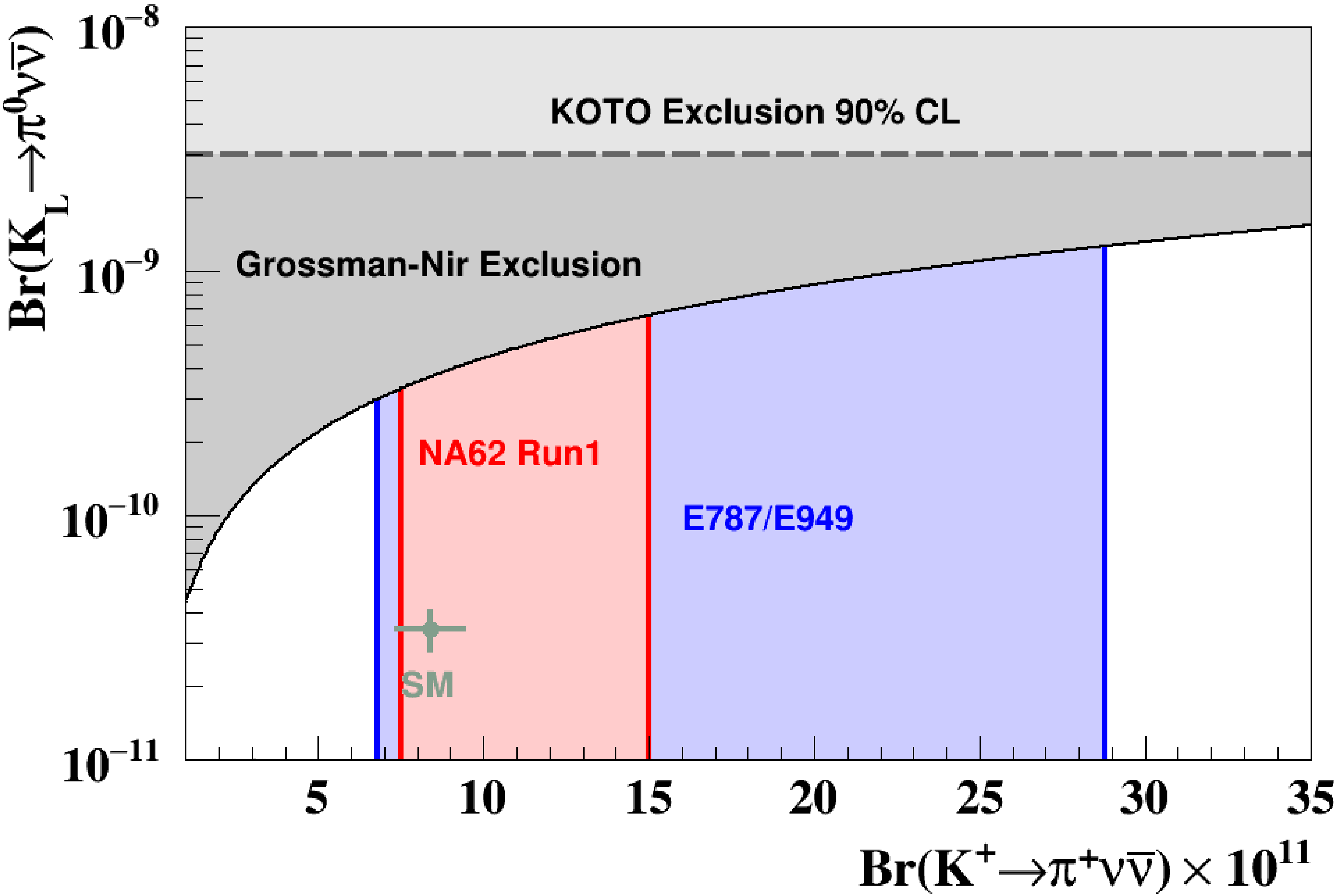
$K^+ \rightarrow \pi^+ \nu\nu$ decay: Historical context



$K^+ \to \pi^+ \nu\nu$ decay: Historical context



Grossman-Nir limit



Summary and conclusions

- NA62 result from the complete Run 1(2016 + 2017 + 2018)
  - Observed events: 1 (2016) + 2 (2017) + 17(2018) = 20 (Run 1)
  - Expected background ~ 0.2(2016) + 1.5(2017) + 5.3(2018) = 7 (Run 1)
  - $Br(K^+ \to \pi^+ \nu \bar{\nu}) = (11.0^{+4.0}_{-3.5}{}_{stat.} \pm 0.3_{syst.}) \times 10^{-11}$(3.5$\sigma$ significance)
  - The most precise measurement of the BR obtained so far
- The result is compatible with the SM prediction within one standard deviation

- Towards the 2021 run
  - NA62 will resume data-taking in 2021
  - Modifications of the NA62 beam line, installation of an additional beam spectrometer station and a veto counter to reduce upstream background
  - New calorimeter downstream of MUV and upstream of the beam dump to further suppress kaon decay background
  - More information can be found in the NA62 SPSC addendum

Zoom link

- Join the link after the meeting for a nice discussion and more information
  - https://cern.zoom.us/j/2390926840?pwd=Q1NrcW5YNlhKZS90U0ZwM0QzeENYQT09